

# The milliJansky $12\mu\text{m}$ Population: First Followup <sup>★</sup>

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## ABSTRACT

We present the first results of our followup programme of optical imaging and spectroscopy of a deep  $12\mu\text{m}$  survey conducted with the ISO satellite (Clements et al. 1999). We find that the objects are typically of fairly low redshift ( $z \sim 0.1\text{--}0.2$ ), but with a tail that extends to high redshifts. The highest redshift object is a previously unknown quasar at  $z=1.2$ . The sample of objects for which spectroscopy has been obtained forms a complete subsample of the original survey with an R band magnitude limit of 19.6. We are thus able to use *accessible volume* methods to determine the luminosity function. We find that the luminosity function is close to the low redshift  $12\mu\text{m}$  luminosity function determined by IRAS (Fang et al., 1998; Rush et al., 1993), but with a possible excess at the highest luminosities, which also correspond to the highest redshifts. This excess is compatible with the rapid luminosity evolution of  $L \propto (1+z)^{4.5}$  claimed by Xu (2000) and suggested by Elbaz (1999) on the basis of number counts. These conclusions remain tentative because of small number statistics at the highest redshifts.

Almost all of the galaxies in this survey are emission line objects. We use the spectra to determine emission line diagnostics for the underlying ionisation source. We find that the majority of objects have HII region-like spectra (roughly 2/3) but there is a significant fraction (about 1/3) that contain an AGN. This confirms suspicions that deep mid-IR surveys will be a powerful way to find obscured AGN. Part of the survey area has been imaged deeply by the INT Wide Field Camera. Nearly all  $12\mu\text{m}$  sources in this area, down to the  $3\sigma$  sensitivity limit of the original ISO survey, have good optical identifications, the faintest being at  $R=23$ . The prospects are thus good for obtaining complete spectroscopy for this sample. With such data we should be able to make a clear measurement of the evolution rate of this population and determine the role of obscured AGN in the mid-IR.

**Key words:** galaxies:infrared, galaxies:starburst, galaxies:surveys, galaxies:evolution, galaxies:active

## 1 INTRODUCTION

The ISO satellite (Kessler et al., 1996) has vastly increased our observational capabilities in the mid- and far-IR, and has ushered in a new series of deep cosmological surveys at these wavelengths (eg. Oliver et al. 2000; Elbaz et al. 1999; Kawara et al. 1998; Puget et al., 1999; Clements et al. 1999).

In the mid-IR these surveys reach flux limits more than 100 times fainter than our previous best surveys with IRAS (Hacking et al., 1987), whilst also attaining substantially improved spatial resolution. They thus represent an important new tool for observational cosmology. They are especially important since there is increasing evidence that much of the star-formation activity in the universe is obscured by dust, which re-radiates the energy absorbed at optical and UV wavelengths into the mid- and far-IR. While the discovery of luminous and ultraluminous infrared galaxies (LIGs and ULIRGs) in the local universe by IRAS was the first hint of the potential importance of obscured emission (see eg. Saunders & Mirabel, 1996, and references therein), it wasn't until the discovery of the cosmic infrared background

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(CIB) (Puget et al., 1996) and large numbers of discrete sources in SCUBA submm surveys (eg. Eales et al., 1999) and ISOPHOT far-IR surveys (eg. Puget et al., 1999) that the cosmological significance became clear. It now seems that such obscured objects might contribute up to 2/3 of the integrated emission in the universe (Gispert et al., 2000) and might thus be the sites for the majority of star formation. Alternatively, a significant number of the obscured sources might be powered by active nuclei, and the sources uncovered by mid and far-IR surveys might thus tell us much about the formation of quasars, and thence the cosmic X-ray background (Almaini et al., 1999).

While much of the emission from obscured sources will be emitted in the far-IR, at wavelengths  $>50\mu\text{m}$ , there are substantial advantages in pursuing surveys in the mid-IR, at wavelengths between 10 and  $20\mu\text{m}$ . These are primarily to do with the limitations of the current generation of instruments. Since ISO had only a 60cm mirror, the angular resolution attainable at long, far-IR, wavelengths is quite poor, leading to problems with confusion and with identifications for followup surveys. These difficulties are largely avoided in the mid-IR. The mid-IR region was also the most sensitive on ISO, with improvements up to 100x over IRAS, while the far-IR typically only reached 10x greater depths, partly as a result of confusion noise (Puget et al., 1999). Despite operating at shorter wavelengths, the mid-IR is still capable of detecting obscured star formation regions. For example, the Antennae galaxy has optically prominent galactic nuclei, but mid-IR images, obtained with ISOCAM (Mirabel et al., 1998), show that the bulk of the star formation resides between these nuclei, in a region of high obscuration. The peak of the mid-IR flux also coincides with the peak of both the  $850\mu\text{m}$  emission, as seen by SCUBA, and the peak of the molecular emission, as revealed by CO observations (Haas et al., 2000, and papers in Hughes & Lowenthal, 2000).

Mid-IR observations, however, do have some problems. These are principally the result of the complex spectral energy distributions (SEDs) in the mid-IR band. For starburst galaxies, which are likely to be the majority of the objects found in a deep mid-IR survey, the SED is dominated by the so-called Unidentified Infrared Bands (UIB), which produce prominent broad features at wavelengths of 6.2, 7.7, 8.6, 11.3 and  $12.7\mu\text{m}$ , and can vary in strength from object to object. Furthermore, there is also the possibility of emission and absorption line contributions, the strongest of which will be the Si absorption feature at  $9.7\mu\text{m}$ . The effect of these features on cosmological surveys in the mid-IR has been extensively studied by Xu et al. (1998). They find that the effects of these features will be more pronounced the narrower the observational passband. While most deep cosmological mid-IR surveys have been conducted in the  $15\mu\text{m}$  band, the present work uses the broader  $12\mu\text{m}$  filter. The Xu et al. modelling clearly shows that this filter will be less susceptible to the effects of the complex SED.

The current results of deep mid-IR surveys with ISO are summarised by Elbaz et al. (1999; but see also Oliver et al., 2000; Serjeant et al., 1997; Clements et al., 1999; Serjeant et al., 2000). Substantial evolution in the number counts, beyond no-evolution extrapolations from the local population, has been found (eg. Elbaz et al., 1999). The meaning of these counts, though, is still unclear. Elbaz et al. (1998), for example, claim that a new population of objects becomes

significant at flux levels of  $< 1\text{mJy}$  at  $15\mu\text{m}$ , producing a distinct bump in the number counts. They suggest that this is a new population of objects at  $z < 1.5$  contributing a substantial amount of the star formation history of the universe. Meanwhile, Xu (2000) suggests that a combination of simple luminosity evolution at a rate of  $L \propto (1+z)^{4.5}$  combined with the colour effects of the UIB features can produce the jump in number counts seen in the data. It is not possible to decide between these possibilities using the existing number count data. The only way to determine the true nature and significance of the sources uncovered by deep mid-IR surveys is to determine their redshifts, and thus to explicitly measure their luminosity function and evolution. Various models of this population can then be explicitly tested. We cannot yet directly obtain redshifts for mid-IR sources in the waveband of detection, but must instead use ground-based optical and/or near-IR observations. Identifications, and spectra, at these complementary wavelengths must thus be obtained.

We here report the first results from identification and redshift measurements for a deep  $12\mu\text{m}$  ISO survey (Clements et al., 1999) conducted using the ISOCAM instrument (Cesarsky et al. 1996) on the ISO satellite. The survey covers a total area of 0.1 sq. degrees made up of four separate subregions separated by several degrees, and reaches a  $3\sigma$  flux limit of  $\sim 300\mu\text{Jy}$ . A total of 148 sources were detected above the  $3\sigma$  limit, though a number of these may still be fragments of brighter sources. Where optical identifications in the US Naval Observatory Catalogue (USNO-A) are available, we can achieve star-galaxy separation using an optical-IR colour-colour method. This relies on the stellar spectra approximating a single temperature black-body, while the galaxies are assumed to have a substantial infrared excess. Very few of the galaxies found in the survey were previously known. Only one object, which was detected by IRAS, had a measured redshift. A full description of this  $12\mu\text{m}$  survey is given in Clements et al. (1999) (hereinafter Paper 1). The goal of the present paper is to present the first results of the followup programme aimed at this survey.

The rest of this paper is organised as follows. In the next section we describe the sample of objects observed, and after that the observations themselves. The results of the spectroscopy are then discussed followed by brief comments on the identification of  $12\mu\text{m}$  sources in two previously blank fields. Discussion of the luminosity function of the  $12\mu\text{m}$  sources and then emission line diagnostics for their power sources follows. We then discuss the nature and significance of this population before drawing our conclusions. An  $H_0$  of  $75\text{kms}^{-1}\text{Mpc}^{-1}$  and  $q_0 = 0.5$  are assumed throughout.

## 2 THE SAMPLE

The target list for the spectroscopic followup was constructed from the list of  $> 5\sigma$  non-stellar sources given in Paper 1. From these we then selected those objects with an optical ID brighter than  $R=19.6$  magnitudes, as cross identified in the USNO-A catalogue. This provides a list of 25 objects. [The object F3\_15, was found to be a star in paper 1 on the basis of its optical/IR colours. This stellar identification was inadvertently missed from Table 2 in that paper,

but was included for the analysis work in that paper. It is thus not part of the basis sample in the current work.]

As part of the INT Wide Field Survey (McMahon et al., 2000) and the UKIRT Mini-survey (Davies et al., private communication), much of Field 1 of Paper 1 was observed in the optical/near-IR, providing UBVRIJK images and photometry. The identifications and fluxes from USNO-A can thus be checked and are found to be broadly correct. The deeper optical data also allows us to go fainter in our identifications of ISO sources in Field 1. We find that all of the  $> 5\sigma$  ISO sources are identified in this field (the faintest is F1.44 which is identified with an R band object with  $R=23.15$ ). We also attempt to obtain identifications for fainter  $3 - 5\sigma$  significance ISO sources using the new optical data. We find good identifications by eye for all except three ISO sources  $> 3\sigma$  within the area covered by the INT WFS image. These three unidentified sources are all of low signal-to-noise, ( $3.5$ ,  $3.0$  and  $3.2\sigma$ ) and so might be residual noise spikes or cosmic hits that have managed to escaped our ISOCAM reduction. The reliability of the source detection, discussed in paper 1, with only 4% of initially detected sources being rejected as spurious cosmic hits, suggests that these may be real sources. We thus conclude that the optical imaging, to about  $R=23.5$ , which identifies 26 ISO sources and fails on these three, has a maximum identification incompleteness of  $\sim 11\%$ . This bodes well for obtaining complete identifications for the  $3 - 5\sigma$  sources in the other three fields with deeper optical imaging, which has now been obtained (Clements et al., in preparation).

The basic properties of the sources observed in this project are given in Table 1.

### 3 OBSERVATIONS

Most of the observations were carried out at the ESO 3.6m telescope at La Silla from Nov. 13 to 15 1999. We used the EFOSC2 instrument. This provides both imaging and long slit spectroscopic capabilities, using filters and grisms (Patat, 1999). The detector is a 2060x2060 thinned Loral CCD which has good sensitivity throughout the optical spectrum. The pixel scale is  $0.157''/\text{pixel}$ . Most of the spectra discussed here were taken using a  $2''$  wide slit, though a few used a  $1''$  slit, and Grism 12, which covers the spectral region from  $\sim 6000$  to  $10000\text{ \AA}$  at  $2.12\text{ \AA}/\text{pixel}$  dispersion. A few objects were also observed in the blue using Grism 11 which covers  $\sim 3400$  to  $7500\text{ \AA}$  at the same resolution. Wavelength calibration was achieved using a He-Ar arc lamp attached to the spectrograph, while flat fielding used a dome flat. The contribution of sky lines to the spectra was calculated by fitting and subtracting a cubic spline function to the spatial direction for each detector row in the dispersion direction. Standard IRAF tasks were used for these procedures. The CCD response function was calibrated out of the spectra using observations of the spectroscopic standard stars LTT9239 and LTT1020. Spectroscopy integration times ranged from 900 to 1800s. Typical observing conditions were for seeing between  $1''$  and  $2''$ , and with reasonable transparency. The conditions, however, were not sufficiently stable to be photometric.

Two objects, F1.0 and F2.0 were observed on a previous run, from 24 to 25 December 1997, which was severely

affected by poor conditions and equipment problems. This was also conducted at the ESO 3.6m using EFOSC2. The observational setup was broadly similar, though a different grism, Grism 1, was used. This covers  $\sim 3200 - 10000\text{ \AA}$  at  $6.3\text{ \AA}/\text{pixel}$ . The observations and data reduction for these objects followed the same scheme described above. The reduced resolution, however, means that these observations cannot be used for emission line diagnostics.

In addition to the spectroscopic observations, R band imaging was also obtained for two objects during the 1999 run. These were F4.2, and F4.11, chosen to be bright  $12\mu\text{m}$  sources, with strong detections in the ISOCAM observations, but without a bright ( $R<19.6$ ) optical identification. The images were taken as a series of four separate 200s integrations each shifted by  $-30''$  in both RA and DEC. The images were flat fielded using an imaging dome flat, and then median stacked with the appropriate shifts taken into account. Residuals left after the dome flat were then corrected by median stacking the images for both objects with each other without the shifts corrected, to provide a secondary, sky flat image.

## 4 RESULTS

### 4.1 Spectroscopic Results

The reduced spectra were all visually inspected and initial classifications, as stars, emission line galaxies and, in one case, a possible absorption line galaxy, were made on this basis. The vast majority of objects turned out to be emission line galaxies. These spectra were further analysed to extract redshifts, determine emission line strengths, and to search for broad emission lines. Redshifts and derived properties are summarised in Table 2. The following method was used to extract spectral properties: first the brightest pixel in a given wavelength range is assumed to be  $\text{H}\alpha$ . Then a composite spectrum, including a background flux constant wrt. wavelength,  $\text{H}\alpha$ , [NII] and [SII] emission lines, is matched to the spectrum. The lines are assumed to have Gaussian shapes, with [NII] and [SII] lines having the same width but different from  $\text{H}\alpha$ . The strengths of the  $\text{H}\alpha$ , [NII] and [SII] lines are allowed to vary, but the ratios of the [SII] and [NII] doublets are fixed at their physical values (Osterbrock, 1989). The assumed redshift is also allowed to vary. The  $\chi^2$  between the model and the observed spectrum is minimised using a downhill simplex method (AMOEBA in IDL). Where a broad line is suspected, an additional model component consisting of an extra  $\text{H}\alpha$  with larger initial Gaussian width is added to see if the  $\chi^2$  is significantly reduced. This is found to be the case in only one object. The results of these fits are given in table 3, as are the results of the spectroscopy more generally. Spectra are shown in Fig 1 and, for the one quasar in the sample, F4.12, in Fig.2.

Given the redshifts we then calculate the  $12\mu\text{m}$  luminosities of the objects in the usual manner. We include a K-correction to account for the effects of the complex spectral energy distribution (SED) in the mid-infrared. The K-correction adopted is a simple linear fit to the models of Xu et al. (1998). Over the redshift range of interest ( $0 - 1.2$ ) the Xu K-corrections can be approximated as  $K = 1.7z$ , using the definition of K-correction from Xu et al. (1998). However, this is the mean K-correction and does not take into

Object	RA (2000)	Dec (2000)	F <sub>12</sub> ( $\mu$ Jy)	R <sub>mag</sub>	Redshift (z)	Log(12 $\mu$ m Luminosity) ( $L_{\odot}$ )	Log(Bolometric Luminosity) ( $L_{\odot}$ )
F1_0	03 05 36.2	-09 31 21.6	12147 $\pm$ 200	17.1	0.113	10.1	11.2
F1_3	03 05 15.1	-09 31 17.6	3835 $\pm$ 99	18.6	0.191	10.1	11.2
F1_4	03 05 05.3	-09 32 07.7	2150 $\pm$ 185	19.5	0.249	10.1	11.2
F1_5 <sup>a</sup>	03 05 24.5	-09 35 50.7	1046 $\pm$ 102	20.2	0.478	10.6	11.7
F1_7	03 05 39.5	-09 31 25.7	968 $\pm$ 241	19.1	0.114	9.0	10.1
F1_9	03 05 35.9	-09 31 43.8	3732 $\pm$ 142	18.6	0.115	9.6	10.7
F1_10	03 05 06.1	-09 32 41.5	1903 $\pm$ 185	17.9	0.113	9.3	10.5
F1_11	03 05 14.9	-09 31 03.8	1324 $\pm$ 113	18.9	0.290	10.1	10.8
F1_12	03 05 28.4	-09 35 17.5	842 $\pm$ 92	16.9	0.461	10.4	11.1
F1_18	03 05 36.3	-09 31 32.2	2190 $\pm$ 171	18.5 <sup>c</sup>	0.113	9.3	10.5
F1_30	03 05 30.7	-09 33 13.4	636 $\pm$ 88	18.8	0.138	9.0	9.7
F1_34	03 05 39.0	-09 38 32.2	563 $\pm$ 115	18.3	0.098	8.6	9.3
F1_48	03 05 11.0	-09 33 10.0	605 $\pm$ 119	19.1	0.120	8.8	9.9
F2_0	03 01 06.1	-10 44 27.5	10479 $\pm$ 260	13.0	0.032	8.8	9.9
F2_3	03 00 37.3	-10 42 51.0	2385 $\pm$ 100	18.8	0.171	9.8	10.5
F2_24	03 00 35.4	-10 43 22.3	814 $\pm$ 118	18.5	0.119	9.0	9.7
F2_80	03 00 39.5	-10 39 43.4	522 $\pm$ 89	19.5	0.093	8.5	9.6
F3_3	03 10 00.9	-08 39 39.2	1760 $\pm$ 95	14.6	M star		
F3_4	03 10 09.1	-08 38 57.2	1682 $\pm$ 105	17.6	0.107	9.1	10.2
F3_5	03 09 44.7	-08 32 55.6	1374 $\pm$ 108	17.0	0.132	9.3	10.4
F3_34	03 09 46.1	-08 32 44.0	639 $\pm$ 105	17.9	0.576	10.6	
F4_1	03 04 03.4	-10 01 18.0	3670 $\pm$ 149	17.9	0.175	10.0	11.1
F4_3	03 03 55.2	-09 56 59.9	3207 $\pm$ 84	16.6	0.171	9.9	10.6
F4_5	03 03 47.3	-09 59 18.2	2481 $\pm$ 215	19.0	0.383	10.7	11.4
F4_6	03 04 06.3	-09 53 47.6	3051 $\pm$ 197	16.6	0.214	10.1	11.2
F4_9	03 03 56.8	-09 57 31.3	1234 $\pm$ 95	17.6	0.171	9.5	10.6
F4_12	03 03 54.7	-09 58 45.6	933 $\pm$ 106	19.1	1.2	12.0	12.7

**Table 1.** Properties of 12 $\mu$ m Sources

Source name is given by catalogue number in appropriate field (F1 to F4), as in Paper 1. Objects already known to be stars from Paper 1 have been excluded. R band magnitudes in field 1 come from the INT WFC survey data, others come from the USNO-A catalogue.

Signal-to-noise ratio for the 12 $\mu$ m detection can be estimated from the flux error. Bolometric luminosity is calculated using the conversion from 12 $\mu$ m to bolometric luminosity determined by Spinoglio et al., (1993) and the classifications from emission line diagnostics. A ‘mixed’ class object is treated conservatively as being an AGN. Where emission line diagnostics are unavailable the object is treated as a starburst. Notes; a: additional object below nominal R band magnitude limit; b: source outside region covered by INT WFC survey, R band magnitude from USNO-A catalogue; c insecure redshift based on absorption feature. All other redshifts based on emission lines.

account the effects of SED differences from one object to another. These differences, though, are smaller in the ISO 12 $\mu$ m band than in any of the other ISO filters used for deep ISOCAM surveys (Xu et al. 1998). The uncertainties produced by this scatter should be less than  $\sim 0.2$  mag, and thus should not have a major effect on the luminosity function we derive from these luminosities.

#### 4.1.1 Notes on Specific Objects

**F3\_3:** This object was classified as a galaxy based on its location on the B-R-F<sub>12</sub> colour/colour diagram (Paper 1). However, spectroscopy clearly shows that the object is an M star. The previous misclassification is probably due to the large molecular absorption bands in the M-star spectrum suppressing optical emission below what would be expected from a simple black-body spectrum.

**F1\_34:** The H $\alpha$  emission line in this object appears to be broad,  $\sim 1000$  km s<sup>-1</sup> (cf. 400 km s<sup>-1</sup> for the other, narrow lines) indicating the likely presence of a Seyfert 1 active nucleus.

**F4\_12:** At  $z=1.2$  this is the highest redshift object in the

sample. It is also the only object in the sample characterised by a clear broad line spectrum, containing emission lines of MgII and AlII/CIH]. There also appears to be a broad emission feature to the blue of MgII which could be due to FeII. The MgII FWHM is found to be 4300 km s<sup>-1</sup> (observed frame). The spectrum is shown in Figure 2.

## 5 BLANK FIELDS

Ten sources from Paper 1 are as yet optically unidentified. At the same time as our optical spectroscopy, we thus also obtained moderately deep images for two 12 $\mu$ m optical blank field sources, F4\_11 and F4\_2. These are shown in Figure 3. In both cases we find plausible faint optical identifications within 7'' of the ISO source position. In the case of F4\_11 the identification is isolated and unambiguous. In the case of F4\_2, however, there would appear to be a group of similar faint objects close to the primary identification. There is thus the potential that the ISO source may be a combination of two, possibly interacting, objects, or that the identification might be one of the other optical sources in the field.

We can obtain an estimate for their magnitude by com-

Object	Redshift	H $\alpha$ EW	[NII] EW	[SII] EW	H $\alpha$ (broad)	Class
F1_3	0.191	104.6	60.7	26.4		HII
F1_4	0.249	41.5	21.0	15.0		HII
F1_5	0.478	50.3	33.4	<48		?, HII*
F1_7	0.114	14.7	4.9	1.8		HII
F1_9	0.115	26.7	11.1	10.0		HII
F1_10	0.113	17.0	6.4	4.3		HII
F1_11	0.290	21.7	35.9	<3.0		M, HII*
F1_12	0.461	54.9	53.0	30.7		SII, SII*
F1_18	0.113	79.1	50.1	24.9		HII
F1_30	0.138	28.1	20.1	2.7		M
F1_34	0.098	9.1	13.6	3.4	26.4	S1
F1_48	0.120	61.3	26.7	21.2		HII
F2_3	0.171	13.25	13.3	8.8		SII
F2_24	0.119	17.3	20.2	17.2		SII
F2_80	0.093	56.9	17.1	18.1		HII
F3_4	0.107	49.6	21.0	13.2		HII
F3_5	0.132	21.2	10.9	A band		HII
f4_1	0.175	35.0	20.9	10.3		HII
F4_3	0.171	14.1	11.9	5.7		SII
F4_5	0.383	46.7	44.8	9.5		M, SII*
F4_6	0.214	11.3	6.6	1.8		HII
F4_9	0.171	A band	A band		?	
F4_12	1.2					SI

**Table 2.** Emission Line diagnostics and Classifications

Emission line equivalent widths and derived classifications for objects where emission line classifications are possible. HII indicates an HII region-like spectrum, and thus an object likely to be powered by a starburst. SI and SII indicate a Seyfert 1 (ie. broad line) and Seyfert 2 spectrum respectively, and thus the presence of, and probable powering by, an AGN. M indicates a spectrum that may be a mixture of HII and Sy2, or may be a LINER – the current limited set of emission lines cannot discriminate between these possibilities. 'A band' indicates that the relevant lines are affected by atmospheric absorption by the A band, leading to uncertain equivalent widths. In most of these cases classification is not possible. '?' indicates that the current measurements or limits to equivalent widths do not permit classification. In some cases there are second classifications indicated by \*. These are classifications which include the H $\beta$  and [OIII] fluxes when they are available. In the case of M and ? classifications these later, more complete, classifications are adopted.

**Figure 1.** Observed Spectra

Spectra for the galaxies observed in this programme. The locations of important features, typically H $\alpha$  and SII, are indicated, and the wavelength range shown is chosen to highlight these features. Spectrophotometric calibration is not fully calibrated so flux values are indicative only. The objects F1\_0 and F2\_0 were observed in poor conditions on an earlier observing run. These two spectra are not flux calibrated, merely divided through by a standard star, so the apparently blue continuum slope is not real.

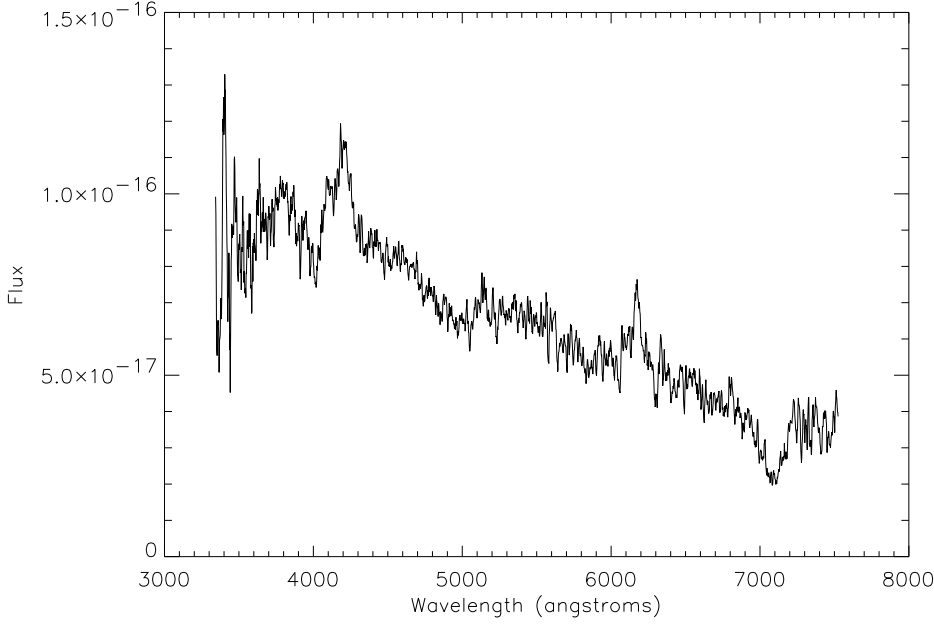
parison with magnitudes of known objects imaged at the same time. We find that F4\_11 has  $R \sim 20$  and F4\_2  $R \sim 22$ . These results are consistent with the results from the INT WF survey data discussed above.

With identifications obtained for these two sources, there remain 8 sources with ISO detections  $> 5\sigma$  that still lack optical identifications. Since these are the objects with the highest 12 $\mu$ m to optical ratios, they are clearly interesting targets. Their optical faintness suggests that they are at

high redshifts, and they are thus likely to be highly luminous. Further observations will be proposed to obtain identifications and redshifts for these, and fainter ISO sources.

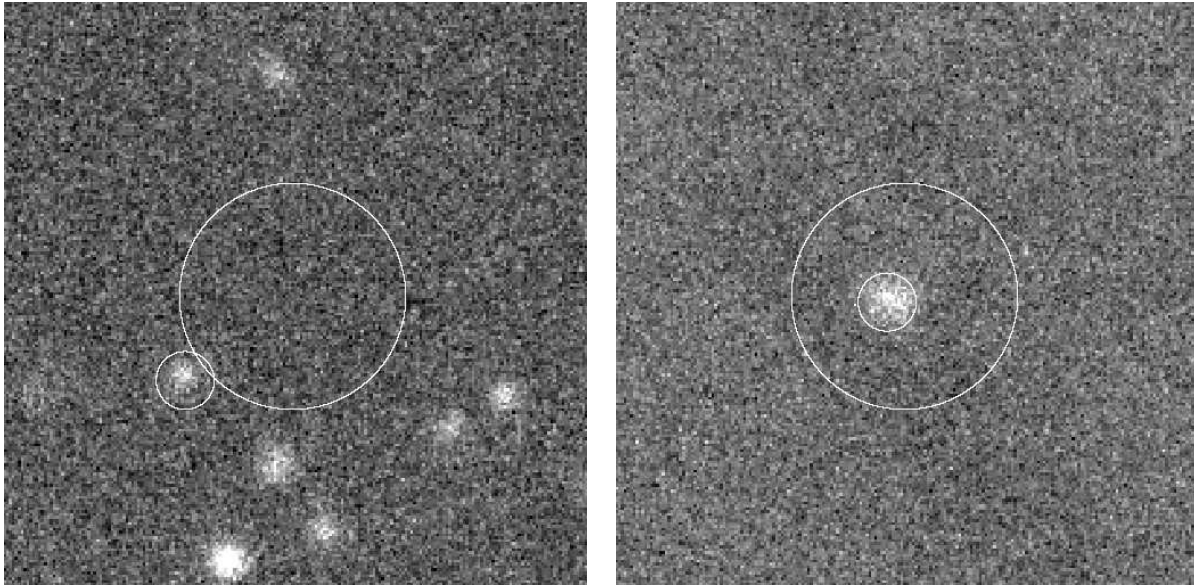
## 6 THE LUMINOSITY FUNCTION

The data presented in this paper provides redshift information for a complete subsample of the 12 $\mu$ m survey. We are



**Figure 2.** F4\_12 Spectrum

Spectrum for the  $12\mu\text{m}$  selected quasar discovered in this survey.



**Figure 3.** R band images of  $12\mu\text{m}$  optical blank fields.

F4\_2 (left) and F4\_11 (right). The images are  $31.4''$  to a side. The nominal position of the ISO source is at the centre of each image. The astrometric accuracy of the ISO observations is  $6''$  ( $2\sigma$ ) (Paper 1), and this is shown by the large circle. A smaller circle highlights the likely identification. The F4\_2 identification has  $R \sim 22$ , F4\_11 has  $R \sim 20$ . See text for details. Images are of similar depths, reaching  $R \sim 23$ . The scaling is linear, chosen to highlight relevant features.

complete to the  $5\sigma$  flux limit of the survey, and to  $R=19.6$  magnitudes for the optical identifications and redshift information. We can thus use the *accessible volume* method (Avni & Bahcall, 1980) to determine the  $12\mu\text{m}$  luminosity function in this sample, whose  $12\mu\text{m}$  flux limit is a factor of  $> 20$  deeper than existing determinations of the mid-IR luminosity function (Hacking et al., 1987). We use the stan-

dard  $1/V_{max}$  method to determine the luminosity function, with the volume determined from the maximum distance at which a source would be detected i.e. the accessible volume. The luminosity function contribution of each object is  $1/V_{max}$  where  $V_{max}$  is given by the redshift at which an object would drop out of either the survey data or the followup programme, whichever is smaller.

Thus:

$$\Phi(L)dL = \sum_i \frac{1}{V_i} \quad (1)$$

where  $\Phi(L)$  is the number of objects  $Mpc^{-1}$  in the luminosity range  $L$  to  $L + dL$  and

$$V_i = \min(V_{opt,i}, V_{12,i}) \quad (2)$$

where  $V_{opt,i}$  is the volume in which the  $i$ th object could have been detected down to the  $R=19.6$  magnitude limit of the optical followup, and  $V_{12,i}$  is the volume in which the  $i$ th object could have been detected down to the 500 $\mu$ Jy flux limit in the original survey. The volumes are calculated taking into account the variable flux depths of the original 12 $\mu$ m survey (see Paper 1).

The luminosity function produced from these considerations is shown in figure 4. As can be seen the luminosity function is a fairly close match to existing 12 $\mu$ m luminosity function determinations based on low redshift IRAS data (see eg. Fang et al 1998). The only substantial excursion from the local luminosity function occurs at the highest luminosities. Since these high luminosity bins are also dominated by the highest redshift objects this might be taken as evidence for evolution. Combining the two highest luminosity bins to provide better statistics (3 objects) at the highest luminosities suggests a  $\sim 3\sigma$  significance difference between the current luminosity function and that derived from IRAS (Fang et al. 1998; Rush et al., 1993). The mean redshift for objects in this bin is 0.7, implying density evolution at a rate of  $(1+z)^8$  or luminosity evolution at a rate of  $(1+z)^5$  with large uncertainties on these exponents. These values are broadly consistent with the evolution in the ultraluminous IRAS galaxies suggested by Kim & Sanders (1998) and with that suggested by Xu (2000) for the 15 $\mu$ m population. However, we as yet have only a small number of objects at the highest luminosities. Indeed, the highest redshift bin contains only one object, F4.12. This is one of only two broad-line objects in the survey as well as being at the highest redshift, so might be an unusual object biasing the statistics. There may also be additional biases entering the data, eg. Malmquist or Eddington bias, since the sample size is so small. These issues will be addressed when the identification programme is complete and we have a larger number of sources.

These hints at evolution in the high luminosity/redshift end of the population can only be confirmed by determining redshifts for the rest of the sample. Since the remaining galaxies are optically faint ( $R > 19.6$ ) there is a strong possibility that substantially more high redshift galaxies will be found, allowing a much better examination of the high redshift and high luminosity end of the luminosity function.

## 7 EMISSION LINE DIAGNOSTICS

The nature of the ionising spectrum in a galaxy can be determined by examining emission line ratios (Baldwin et al., 1981). Standard ratios include  $H\alpha/[NII]$  and  $H\alpha/[SII]$ , which can be determined for most of the objects in the current sample, as well as  $[OI]/H\alpha$ ,  $[OIII]/H\beta$  and  $[OII]/H\beta$ . These latter ratios are not available for most of the objects in the sample since our spectral range did not extend far enough

into the blue, or go deep enough to detect the weak  $[OI]6300$  line. Consideration of the standard emission line diagnostic plots shows that we can attempt a classification using just the  $H\alpha$ ,  $[NII]$  and  $[SII]$  lines we have for the majority of the objects. Our classification diagram is shown in Figure 5. On this basis we find that the majority of our 12 $\mu$ m sources (11/16 where appropriate data is available) have HII region-like spectra ie. are powered by starbursts, while 4/16 have Seyfert2-like spectra ie. contain and may be powered by active nuclei. Two further objects have broad line Seyfert1-like spectra, producing a total of 6/18 objects that contain AGN. Three objects are not clearly classified by this technique and could be composite objects or LINERs.

We can extend this classification scheme for the four objects at high enough redshift and with sufficient signal-to-noise in their spectra to detect  $H\beta$  and  $[OIII]$ . Of these objects only one is fully classified using just  $H\alpha$ ,  $[NII]$  and  $[SII]$ . This object, F1.12, is classified as a Sy2 by both methods. Of the other three objects where we can use  $H\beta$  and  $[OIII]$ , F1.5 was previously unclassified due to a poor  $[SII]$  detection, and the others, F1.11 and F4.5, have mixed classifications. Once  $H\beta$  and  $[OIII]$  ratios are included we find that F1.5 and F1.11 appear to be starbursts (ie. HII-region-like). F4.5 appears to have a confused classification, with  $[OIII]/H\beta$  vs.  $[SII]/H\alpha$  indicating an HII region spectrum, and  $[OIII]/H\beta$  vs.  $[NII]/H\alpha$  indicating a Sy2 spectrum. On further examination it appears that the  $[SII]$  line strength may be underestimated due to a sky absorption feature at the extreme red of the optical band ( $\sim 9300\text{\AA}$ ). We thus tentatively conclude that it is in fact a Sy2.

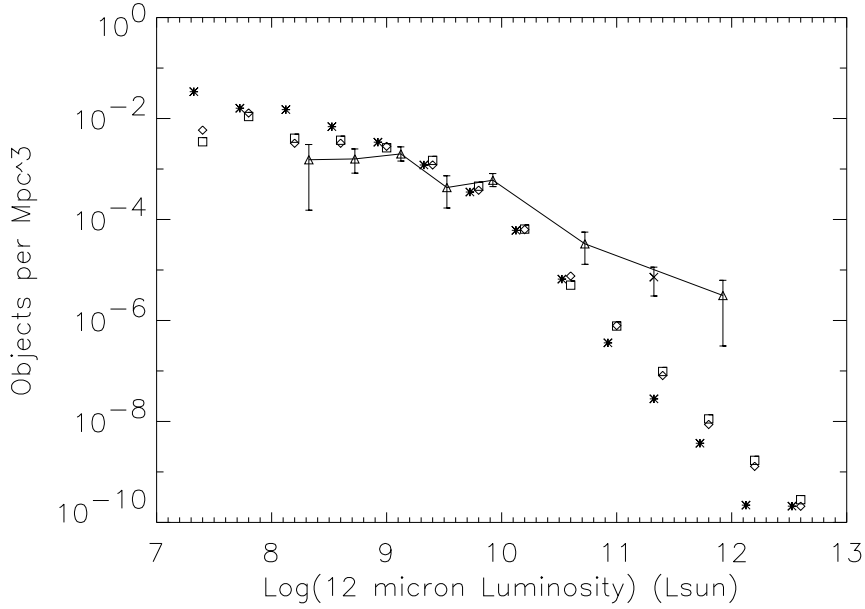
The final tally is thus 14 starbursts, 7 AGN (Sy1 and Sy2), 1 mixed and one unclassifiable. Of the objects where we have a firm classification, 1/3 (7/21) are AGN-type and 2/3 (14/21) are starbursts. We find no significant difference between 12 $\mu$ m luminosities of the two classes, HII and Seyfert, though the most luminous objects are from the Seyfert class.

The Rush et al. (1993) sample of local 12 $\mu$ m selected objects had an AGN fraction of 13%, so the larger fraction we have found here, 33%, may represent some evolution in the population. Alternative explanations, such as different K-corrections between AGN and non-AGN containing objects, greater prominence in the optical for AGN objects, are also possible. These possibilities will be investigated when the identification programme for the complete 12 $\mu$ m survey is finished.

## 8 DISCUSSION

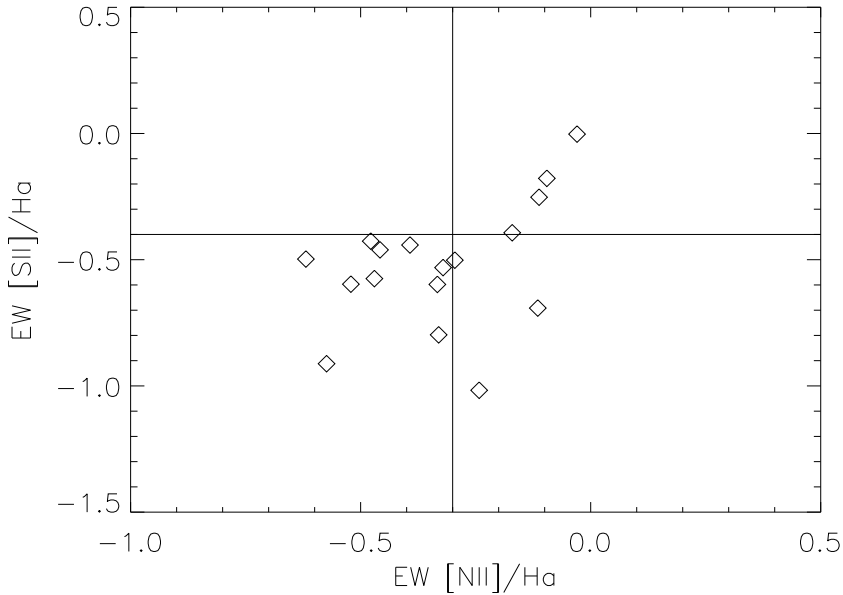
### 8.1 Physical Associations

If we examine the redshift distribution, we find several clumps of objects that appear to group in redshift. These include an apparent group around  $z=0.11$  in field 1, and around  $z=0.17$  in field 4. We can test the reality or otherwise of these associations by examining the positions of the objects on the sky. In field 1 we do indeed find that the objects F1.0, F1.7 and F1.9 appear to have a close physical association. They form a small group covering a region  $\sim 1$  arcminute across, corresponding to  $\sim 100\text{kpc}$  at  $z=0.11$ , using our assumed cosmology (see Fig. 6). These objects may



**Figure 4.** The  $12\mu\text{m}$  Luminosity Function

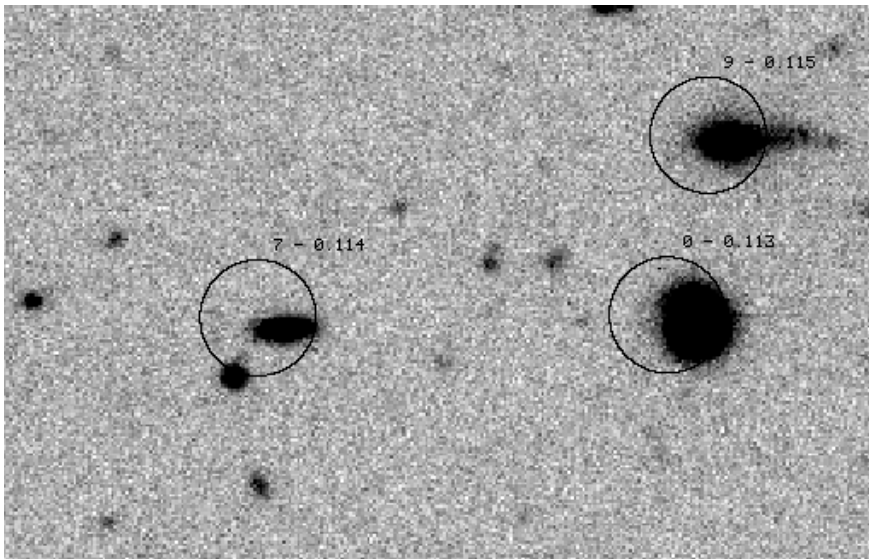
The  $12\mu\text{m}$  luminosity function from Fang et al. 1998 (open squares and diamond for two different corrections to the local density field), Rush et al. 1995 (with luminosity divided by a factor of 1.5 to correct for photometric problems from the use of ADDSCAN data (Alexander & Aussel, private communication)) and from the present work (triangles joined by a line). Note the similarities between the older, IRAS LF determination and the present, ISO determination, and the possible departure at high luminosities which equate to high redshifts. Also shown (X) are the last two bins of the new luminosity function combined to provide a better determination of the evolution at the highest redshifts.



**Figure 5.** Emission Line Diagnostics

Starburst-type objects will lie in the lower left corner, AGNs in the upper right. Objects in the lower right corner receive a mixed classification, and may be composite objects or possibly LINERs. The broad line objects, F4\_12 and F1\_34, are not plotted on this diagram.





**Figure 6.** Group of Objects in Field 1

Circles show the 6 arcsecond  $2\sigma$  astrometric errors on the ISO source position. Text indicates the number of the source in the field 1 list and its redshift. Image is 100 by 66 arcseconds. Note also the disturbed morphology of source F1\_9. North is up and east is to the left. Scaling is linear, and chosen to highlight relevant features.

thus be part of a small group or weak cluster. One other object in field 1 is at roughly the same redshift, F1\_10 at  $z=0.113$ . It is much further away on the sky, 7.5 arcminutes, corresponding to 750kpc. It might thus be part of some weak larger scale structure, but this is difficult to assess with the small numbers of redshifts we have. A simple analysis, using the luminosity function derived in section 6, suggests that the association of F1\_10 with the other three objects is only marginally significant, at  $\sim 90\%$  level.

In field 4 we find that F4\_9 and F4\_3 are close in both redshift (difference  $< 0.0005$ ) and on the sky (39 arcsecond), with a separation corresponding to 94kpc at  $z=0.17$ . They are thus likely to be a close pair of galaxies. F4\_1, in contrast, is significantly further away in both redshift (0.004 in  $z$ ) and angular separation (4.8 arcminutes). It is thus unlikely that there is a strong physical association between F4\_1 and the other two objects.

It is thus possible that 5 of our  $12\mu\text{m}$  sources appear in two groups, though better statistics are needed to determine if the correlation function of  $12\mu\text{m}$  selected objects is any different from optically selected, normal galaxies.

## 8.2 Bolometric Luminosities

Spinoglio et al. (1995) found a correlation between  $12\mu\text{m}$  luminosity and bolometric luminosity. The basis for this correlation was argued to be that the wavelength is a ‘pivot point’ between the optical emission, which rises more slowly than linearly with bolometric luminosity, and the mid- to far-IR, which rises more rapidly than linearly with bolometric luminosity. They also found that the constant of proportionality relating  $12\mu\text{m}$  and bolometric luminosity is different for starburst and AGN sources — thus  $L_{\text{bol}} = 14L_{12}$  for starbursts and  $L_{\text{bol}} = 5L_{12}$  for AGNe, where  $L_{12} = \nu(12\mu\text{m})L_{\nu}(12\mu\text{m})$  in solar units. If we assume that our optical classifications

of these objects genuinely identify the source of their luminosity, then we can calculate the bolometric luminosity of the sources. These are given in Table 2. We find that the typical bolometric luminosity for our  $12\mu\text{m}$  sources is around  $10^{10.5}L_{\odot}$ . The population of mid-IR sources so far uncovered would thus appear to have relatively moderate luminosities, and to not represent any substantial new population of dust-enshrouded starbursts or AGN. Our highest luminosity source, F4\_12, however, turns out to have a bolometric luminosity of  $10^{12.7}L_{\odot}$ , approaching that of Hyperluminous infrared galaxies. Since this is the highest redshift object in the sample, and our luminosity function analysis seems to indicate strong evolution at high redshifts or high luminosities, then one can speculate that this might be the first member of a lurking population of obscured high luminosity systems that we have yet to uncover. Completion of our identification programme can test this idea.

## 8.3 The Nature and Evolution of the $12\mu\text{m}$ MilliJansky Population

Low luminosity  $12\mu\text{m}$  selected sources appear to be similar to the local samples. We find that about 1/3 of them contain AGNe while the remainder are powered by starbursts. These fractions are somewhat higher than those discussed by Rush et al. (1993). At the highest luminosities there are hints of strong evolution being detected, but these are currently dominated by small number statistics. With deeper observations we will not only be able to confirm the presence of evolution but also test claims based upon the  $15\mu\text{m}$  surveys that a substantial new population of objects becomes significant at the  $\sim 1\text{mJy}$  flux level (eg. Elbaz et al., 1998; Aussel et al., 1999). It should be noted that selection of objects at  $12\mu\text{m}$  is much less affected by K-corrections due to the complex mid-IR spectral energy distributions of star-

forming galaxies and AGN (Xu et al., 1998) than selection at  $15\mu\text{m}$ . It has been suggested (Xu, 2000) that the bump in  $15\mu\text{m}$  number counts at  $\sim 0.4\text{mJy}$  is entirely due to this K-correction effect and not due to any new population. While the current survey is working at somewhat brighter fluxes we find no clear evidence for such a population. However, if such sources are optically faint, whether intrinsically or as a result of their redshift, they may well have been missed by the optical selection criterion. Completion of the optical identifications and redshift measurements for all the objects in the survey is needed to test these claims and is thus a high priority.

#### 8.4 Future Prospects

The present paper is only the first step in following up the galaxies found in this  $12\mu\text{m}$  ISO survey. We have here discussed the results of redshift measurements on 26 of the 36 galaxies with fluxes above the  $5\sigma$  flux limit of our survey, forming a complete subsample with  $R < 19.6$ . While we are able to obtain interesting conclusions, they are clearly limited by small number statistics, and we are as yet unable to study objects with a large  $F_{12}/F_{\text{opt}}$  ratio (eg. F4.2 which has  $F_{12}$  of  $3.6\text{mJy}$ , but an  $R$  mag. of  $\sim 22$ ). Completing the redshift observations for the  $10 > 5\sigma$  sources so far unobserved is clearly a high priority. In field 1, where we have deeper optical data, nearly all of the  $12\mu\text{m}$  sources are identified with objects brighter than  $R=23.2$ . If this is representative of the rest of the sample, then complete identifications and spectroscopy should be fairly easy to obtain. Perhaps more interesting is the prospect of extending our redshift observations to fainter  $12\mu\text{m}$  fluxes. If we go to a  $4\sigma$  detection limit, rather than  $5\sigma$  we would include  $\sim 45$  more sources. All of these objects, again, are detected in our deep optical observations of Field 1, so such a study is eminently feasible, given deeper optical imaging and a moderate amount of time for spectroscopy. We will thus be able to substantially increase the number of redshifts we have for faint  $12\mu\text{m}$  sources, and will be able to place the tentative conclusions of the present paper on a much firmer footing. Such observations will make an excellent parallel study to the  $15\mu\text{m}$  surveys also underway (eg. Oliver et al. (2000); Elbaz et al. (1999)).

#### 9 CONCLUSIONS

We have obtained spectroscopy for a complete  $R < 19.6$  subsample of our  $12\mu\text{m}$  survey with the ISO satellite. The redshifts of these objects range from 0.032 to 1.2, with derived bolometric luminosities ranging from  $10^{9.3}$  to  $10^{12.7} L_{\odot}$ . There is tentative evidence for strong evolution at the high luminosity and/or high redshift end of the luminosity function. We find that 1/3 of these sources contain an AGN, while the rest seem to be powered by starbursts. At this stage our conclusions are limited by small number statistics, but there are very good prospects for extending the identification programme for this survey, and thereby allowing stronger, more definitive conclusions to be drawn.

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